ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 9 (2011) 528–537
Engineering Procedia

TRIZ Future Conference 2007

Applying TRIZ for systematic manufacturing process innovation: the single point incremental forming case

Joost R. Duflou *, Joris D'hondt

Katholieke Universiteit Leuven, Mechanical Engineering Department, Celestijnenlaan 300A, 3001 Heverlee- Leuven, Belgium

Abstract

Manufacturing processes are often based on physical principles characterised by a limited applicability window. Enlarging these windows is one of main targets of manufacturing process research activities. Technical and physical contradictions are typically encountered when conducting such research. This paper describes a case in which TRIZ principles were used to systematically identify opportunities for process innovation in the domain of emerging flexible forming methods. The TRIZ principles of physical conflict resolving have been applied to improve the performance of Single Point Incremental Forming.

Keywords: Incremental forming; SPIF; Physical conflict resolving;

1. Introduction

Manufacturing processes, be they based on material removal, material growth or deformation principles, are typically characterised by limitations imposed by the underlying physical principles. Maximum achievable feed rates, maximum thickness or hardness of raw materials that can be processed, and achievable maximum accuracy levels are just some examples of such limitations. These boundaries in the multi-dimensional space determined by the relevant process parameters are often referred to as the process window. Overcoming process limitations, and thus expanding the process window, can be achieved by introducing totally new manufacturing principles. TRIZ can play an important role in such fundamental innovations. In reference [1] it is demonstrated how, for the domain of sheet metal cutting, the consecutive development stages correspond well to development trends recognized in TRIZ, illustrating that the methodology could be applied to systematically identify innovation opportunities. However, in an early development stage of a new technological S-curve, the core objective of most manufacturing engineering research is to enlarge the process window for a given manufacturing principle rather than to identify fundamentally new process technologies. The process limitations to overcome in this kind of research are typically corresponding to technical or physical conflicts that can also be systematically dealt with using a TRIZ approach.

* Corresponding author.
E-mail address: joost.duflou@mech.kuleuven.be .

doi:10.1016/j.proeng.2011.03.139

In this paper such a systematic process innovation procedure is illustrated by means of the case of Single Point Incremental Forming (SPIF). This emerging flexible forming method is in an early state of development and a large number of process variants are currently being studied in the international manufacturing research community [2].

As will be illustrated in this article, applying TRIZ based problem solving, supported by Axiomatic Design (AD) analysis [9] [10] [11], allows to provide direction for this research effort, leading to significant performance improvements.

In the following sections the SPIF process is briefly explained (Section 2), the principal conflicts limiting the process applicability are identified (Section 3) and a possible process design solution is formulated (Section 4). The achievable performance improvements have been verified and are summarized in Section 5.

2. SPIF process description

2.1. Manufacturing principle

Single point incremental forming has emerged in the past few years as an innovative and flexible sheet metal forming technology, fulfilling the need for producing prototypes and small batch production of sculptured sheet metal parts. In this process a spherical tool moves along the contours of the part to be formed according to a programmed tool path, while forming the sheet metal blank, which is clamped into a generic rig, into the desired shape by localized deformation [2] (see Figure 1).

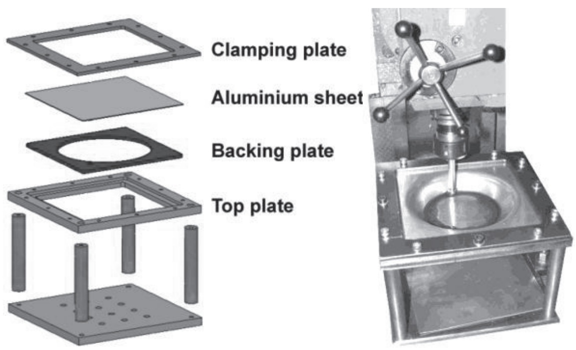


Figure 1: SPIF set-up with exploded rig view.

Unlike conventional sheet forming techniques, SPIF allows to form a wide variety of shapes in a short lead-time and at low cost by employing conventional CNC machinery and without requiring specific tooling. The clamping system used for holding the sheet metal blank is reusable. Where excessive unwanted deformations need to be avoided near the upper surface of the part being formed, a tailored backing plate may be used. This is however not a mandatory feature of the process.

2.2. Process limitations

The omission of a dedicated die significantly increases the flexibility of the process, since producing a die set typically requires approximately two months of lead time. However, this increase in flexibility comes at a price: the process is characterised by a relatively low accuracy, which limits the application range. Allwood et al. [3] investigated the impact of the process window on the applicability of the process, concluding that the limited accuracy forms a major obstacle for wide commercial use. Increasing the achievable tolerance levels therefore forms a major target for ongoing research dedicated to this process. Figure 2 depicts some typical dimensional errors to be expected from SPIF.

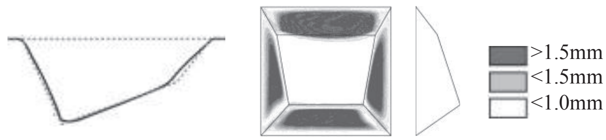


Figure 2: Example of dimensional errors occurring in SPIF generated parts: cross section and top view with error indication.

2.3. Accuracy improving measures

A number of process variants have been suggested to overcome the accuracy problem. These are typically based on the reintroduction of counter pressure under the metal sheet being processed, mimicking the presence of a (partial) die. The best known process variant is described by Matsubaru as Backward Bulge forming [4], and is also often referred to as Two Point Incremental forming (TPIF) [2]. In this process the sheet is formed over a (partial) die that can in some cases be manufactured on the actual forming platform from relatively soft materials. Compared to conventional forming, this process variant still offers improved flexibility. Compared to SPIF however, TPIF does not easily allow two side processing or correcting toolpaths based on metrological feedback.

Allwood [5] and Meier [6] suggest enhanced SPIF systems, respectively using a 3- and 5-axis positioning system for a counter pressure tool. The counter pressure tool is similar in shape to the forming stylus and is generic in nature. It is obvious that synchronising the double contact point in such a way that excessive forces can be avoided, significantly increases the complexity of the process control. No successful implementation of this principle can be demonstrated today.

3. Problem identification

Starting from the observations in Section 2.2 the SPIF process was analysed in order to identify the underlying system conflicts. Two methods were used for this purpose. First an Axiomatic Design analysis [7] was used to identify deficiencies in the design parameter selection corresponding to the present SPIF implementations. This facilitated the identification of relevant conflicts between subsystems of the manufacturing process in a Su-Field analysis.

3.1. Axiomatic design analysis

The mapping of functional requirements (FR) to engineering design parameters (DP) is illustrated in Fig. 3.

As becomes clear from this graphical representation, the basic SPIF process does not provide any degrees of freedom to control the unwanted plastic deformation in non-supported workpiece regions where high stress levels can be reached during the forming process. Neither does the SPIF process provide a solution for the limited formability of specific categories of materials, like high strength Mg or Ti-alloys at ambient temperature. As such the process design is incomplete, and additional system components would have to be added to provide sufficient engineering parameters for a well-optimised design.

In Fig. 4 the equivalent FR-DP mapping is depicted for the TPIF process variant. The relations between both spaces illustrate that the independence axiom [7] is not fulfilled by the TPIF design parameter choice. Included in this figure are also the additional relations with the functional requirements when a heating system for the complete workpiece would be added to the process setup. It is clear that the degree of coupling is further increased.

The compliance check with the independence requirement as formulated in the Axiomatic Design theory thus indicates that, even if one would be willing to reduce the flexibility of the incremental forming process by reintroducing a partial or full die as a counter pressure system, this does not result in a favourable process design. An alternative enhancement of the process setup is thus required.

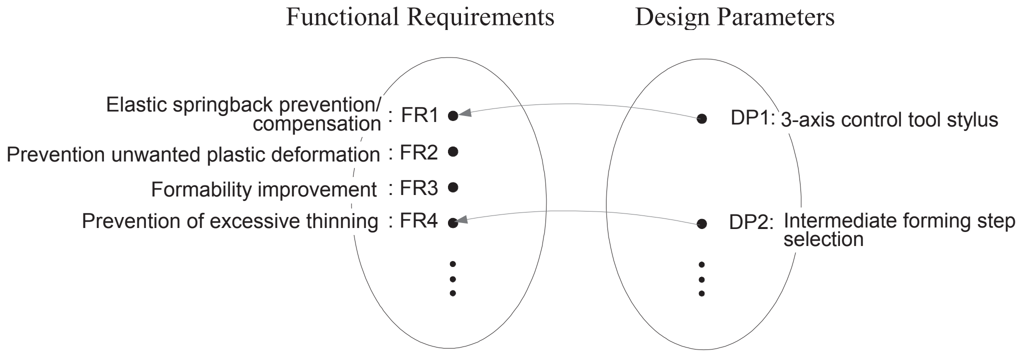


Figure 3: Functional requirement to design parameter mapping for basic SPIF.

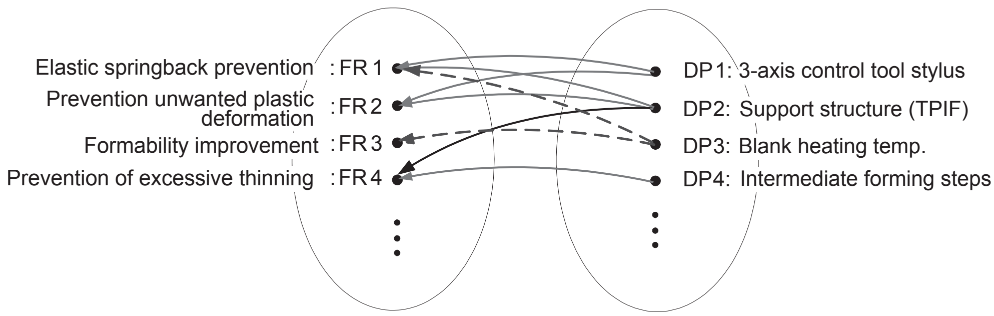


Figure 4: Functional requirement to design parameter mapping for the TPIF process variant, with indication of the impact of adding a preheating system to the setup (dashed arrows).

3.2. Su-Field analysis

A Su-Field analysis provides deeper insight in the system conflicts to be resolved. A summary of such an analysis is provided in Fig. 5.

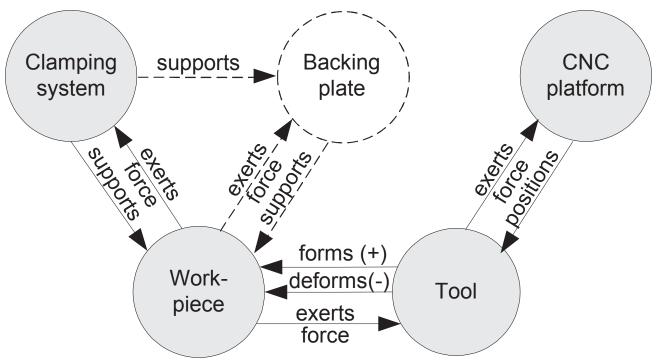


Figure 5: Substance-Field analysis overview for the subsystems in a basic SPIF setup.

Conflicting relations can be detected in the interaction between the workpiece and the tool. While a local, controlled plastic forming effect in the tool contact zone is the target of the process, unwanted deformations are often simultaneously introduced in workpiece areas not in contact with the tool. These deformations are the result of excessive stress levels linked to process force transmittance to the clamping system (or backing plate support system).

4. Physical conflict resolving

The problem to be solved can thus be formulated as follows: "Identify a system enhancement that allows to locally form the workpiece sheet material without introducing unwanted plastic deformations in the area not in contact with the tool".

In order to achieve this without the reintroduction of a die set (TPIF), the following strategies could be applied:

1. Lower the yield strength of the workpiece material in the processed area (in order to lower the process force level).
2. Limit the hardening behaviour of the workpiece material in the processed area (for the same reason).
3. Increase the yield strength of the workpiece material in the non-processed area (in order to avoid plastic deformation)
4. Maximise the hardening behaviour of the material in this non-processed area (for the same reason).

It is obvious that strategies 1 and 2 are not compatible with measures 3 and 4, leading to the identification of a clear physical conflict: how can the material be chosen to be ductile on the one hand and stiff and hard to deform on the other hand?

Calling upon the often used technique of preheating the material in order to improve the formability and to lower the process forces (see Figure 6) does not provide a solution here. Indeed, while this would form an implementation method for strategies 1 and 2, it would simultaneously result in a weakening of the material in the zones where unwanted plastic deformation is to be avoided (in conflict with strategies 3 and 4).

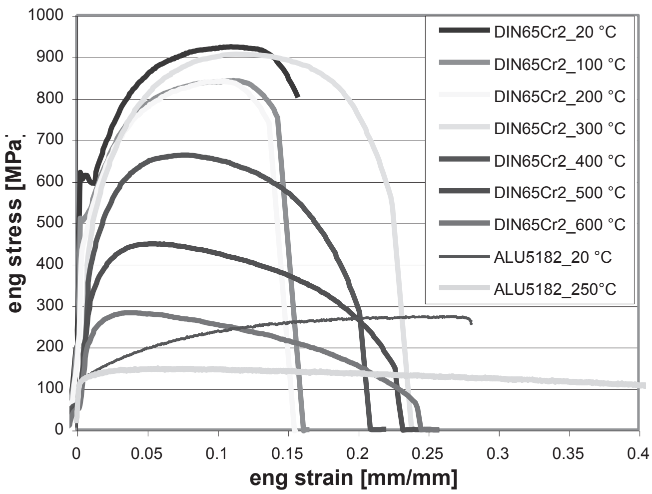


Figure 6: Influence of temperature on constitutive law for DIN65Cr2 and Al 5182

TRIZ provides an answer through the principles of separation:

1. Separation in space
2. Separation in time
3. Separation between the whole system and its parts
4. Separation based on different (external) conditions

Combining the contradicting requirements of the four strategies can indeed not be achieved for the complete workpiece simultaneously. However, through the principles of separation in space and time, it can be envisaged to differentiate the material properties between the different zones of the workpiece. Since the contact zone is constantly changing, this localisation has to be applied dynamically. Applying heating of the sheet material in a localised (principle 1) and dynamic (principle 2) fashion was therefor considered as a promising process enhancement strategy. This would require local heat supply during the process, rather than a uniform preheating of the sheet metal blank. Furthermore, in order to assure a local heated spot in the processing zone only, active cooling of the surrounding area is also required, resulting in a clear temperature gradient between the tool contact zone and the workpiece area where uncontrolled deformation is not desirable.

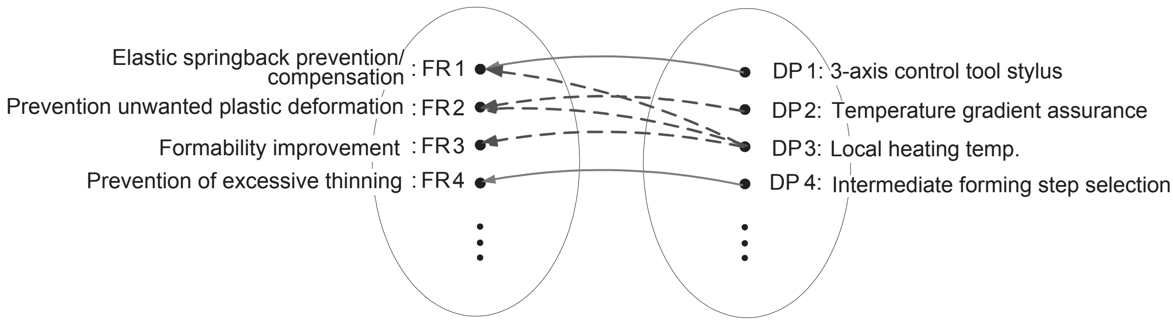


Figure 7: Mapping of functional requirements and design parameters for the modified SPIF process, with indication of the effects of the added design parameters associated with local dynamic heating and active cooling (dashed arrows).

By localising the heat input according to separation principles 1 and 2, automatically distinction is made between the whole workpiece (which is kept at near ambient temperature), and the tool contact zone (where the temperature can be significantly increased depending on the applied material and required differentiation), as suggested by separation principle 3. Furthermore, the heat supply can be decided upon taking the workpiece geometry into account. For example, in the vicinity of strong slope changes, maximal use can be made of the heating effect and the resulting temperature gradient, while in areas where a flat bottom surface needs to be formed, the heating could be switched off all together (separation principle 4). The effects of introducing localised, dynamic heating to the process design parametrization are depicted in Fig. 7.

As can be concluded from this AD analysis scheme, the introduction of localised heating is expected to contribute to the formability improvement objective. It is also envisaged that for most materials local elastic springback effects could also be reduced by an appropriate temperature increase. Lowering the total process force level, by a significantly reduced yield strength and hardening effect in the tool contact zone, results in lower stress levels in non-processed zones of the workpiece, eliminating unwanted deformation effects. The parameter mapping in Fig. 7 indicates that a decoupled design [7] has been achieved, which forms an improvement from the coupled design of Fig. 4. A truly uncoupled design would require independent control over the temperature level in function of an optimised formability, a minimised springback and a minimised stress level. Since these requirements have to be fulfilled simultaneously and at the same location, identifying an uncoupled design is not obvious.

5. performance improvements

An experimental setup was built according to the principles of local, dynamic heating identified above (see Figure 8).

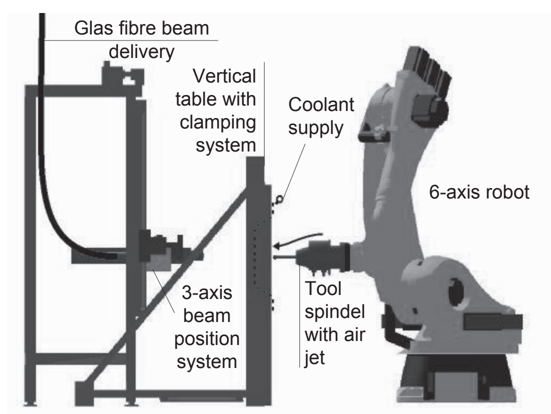


Figure 8: Experimental setup for SPIF with localised dynamic heat support

The setup consists of a 6-axis robot and an NdYAG laser system with beam delivery through a glass fibre and a focusing head mounted on a 3-axis positioning system. Robot and positioning system are steered by a common control system. While the robot system is used to execute the incremental forming movement of the tool, the beam positioning system assures a well-synchronised movement of the heated spot along with this tool path. The independent movement of the beam positioning system allows a relative offset of the heating point compared to the tool position in order to optimise the temperature field (Fig. 9).

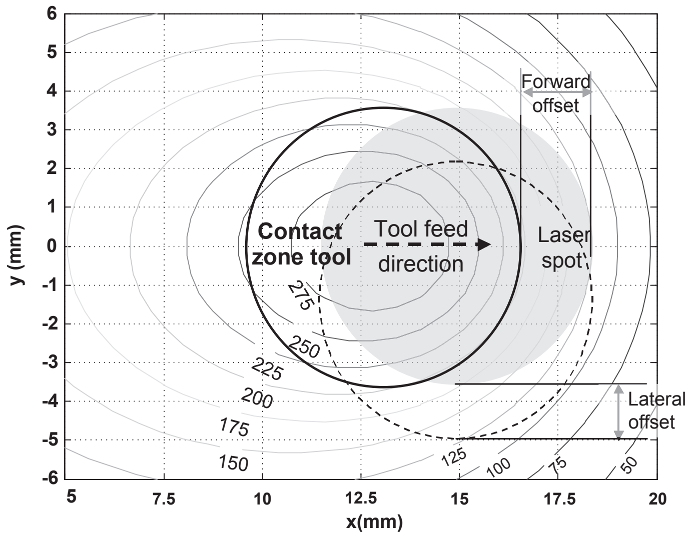


Figure 9: Relative positioning of tool contact zone and laser spot

A cooling system is used to guarantee the required temperature gradient and thus avoids the gradual heating up of the entire workpiece.

An experimental program run on this setup allowed to demonstrate the following process performance improvements.

5.1. Process force reduction

Using a force sensor mounted on the robot wrist, the reduction of the process forces for SPIF with dynamic heating support, compared to forming at ambient temperature, could be demonstrated (Fig. 10). From this figure it can be observed that, by choosing an appropriate heating temperature, the dominant force component parallel to the tool axis can be reduced to approximately 50%. It is obvious that the resulting stress levels in the vicinity of the tool contact zone are reduced accordingly, effectively reducing the areas in which the yield strength of the material is exceeded. This can be expected to lead to systematic accuracy improvement, as illustrated in the next section.

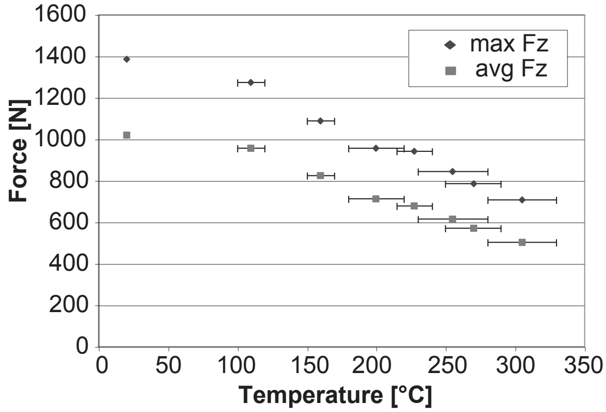


Figure 10: Forces measured along the tool z-axis for Al5184 in function of the local heating temperature in the tool contact zone.

5.2. Accuracy improvement

Fig. 11 shows the effect of localised heating on the overall accuracy of the workpiece. It should be noted that in the underlying experiment constant heating was applied. On one hand this leads to an improved approximation of the intended CAD geometry, e.g. in Zone A. However, the local heating also results in groove formation in Zone B (the bottom surface of the part not being processed). Timely switching off the heating, in accordance with separation principle 4, could allow to minimise this effect.

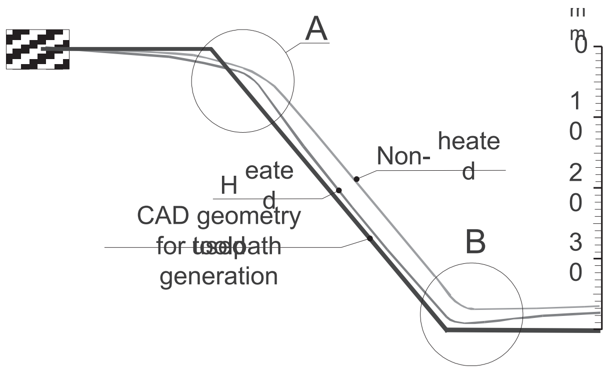


Figure 11: Accuracy improvement for a conical workpiece with indication of the envisaged CAD geometry used for toolpath generation.

5.3. Formability improvement

Some materials are known for their limited formability under ambient temperature conditions. TiAl6V4 sheets of 0.6mm thickness were used to compare the formability behaviour under dynamically heated conditions with test results obtained at ambient temperature.

Conical shapes with maximum outer diameter 140mm and increasing wall angle were formed using a backing plate with a 180mm aperture. A spiralling toolpath with a continuous incremental step size (pitch) of 0.5mm was used. The initial feed rate of the robot was set to 1000mm/min. This feed rate was varied for some of the dynamically heated tests to assure a constant energy input density for different laser spot diameters (tests with diameter 14 and 15mm in Table 1).

Non-heated		Heated			
wall angle [°]	obtained result	wall angle [°]	spot size [mm]	energy input [J/mm²]	obtained result
30	OK	45	12.0	0.875	OK
35	failed	50	12.0	0.875	OK
32	OK	55	12.0	0.875	failed
34	failed	53	12.0	0.740	OK
33	failed	55	12.0	0.740	OK
		57	12.0	0.740	failed
		56	12.0	0.740	failed
		56	14.0	0.740	OK
		57	15.0	0.740	failed

Table 1: Formability test results for 0.6mm TiAl6V4.

At room temperature (20°C), it was possible to form cones with slope angles up to 32°, whereas tests with a higher wall angle resulted in cracks appearing before a 30mm depth was reached (see Table 1).

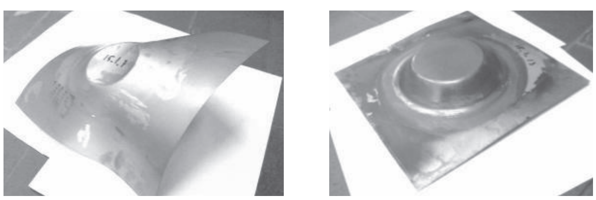
With an effective power input of less than 200W the maximum forming angle could be substantially shifted. Varying the spot diameter and the energy input level successfully allowed to form cones with slope angles up to 56°. Optimising the temperature field by adjusting the cooling conditions may allow to further increase this limit.

Similar tests demonstrated an increase in formability for materials with a higher formability at room temperature as well. 65Cr2 sheets with a 0.5mm thickness could, for example, be formed into cones with slope angles up to 57° at room temperature without any cracks appearing before a 40mm depth was reached.

The same material, tool and process parameters were used to produce samples under dynamic heating conditions. Assuring a process temperature in the forming zone of approximately 350°C, parts were made with a wall angle of 64° without any part failure occurring. According to the sine law approximation [2], and in terms of principal strain, the wall angle increase of 7° corresponds to a strain increase of 44.5%.

5.4. Residual stress reduction

Warm forming of sheet material is known to result in lower elastic springback [8]. Question was whether dynamic, localised heating would yield similar results, or might, on the contrary, lead to residual stresses that could cause additional elastic deformations upon unclamping or trimming of the workpiece.



A B

Figure 12: Obtained workpiece geometry for non-heated (A) and heated process variants (B) after unclamping.

Figure 12 depicts the results of tests conducted with TiAl6V4 after unclamping of the test specimen. While for the left part (A) a 30° cone was created at ambient temperature conditions, for the part at the right a 50° cone was generated using dynamic local heating support. The residual elastic stress levels, that visibly deform the workpiece upon unclamping when cold formed, are significantly reduced in the heat supported process variant.

6. Conclusions

In this paper the applicability of TRIZ analysis and problem solving techniques for the systematic enlargement of the manufacturing process window of a newly emerging forming technique was illustrated. The physical conflict resolving separation principles lead to the specification of a process variant that proved to offer superior performance results compared to the original process capabilities. Taking the favourable results obtained in preliminary tests into account, a patent was filed for the enhanced SPIF variant based on localised, dynamic heating.

Acknowledgments

The authors would like to acknowledge the financial support of the Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT) and the Belgian Federal Science Policy Office (Contract P5/08).

References

[1] Duflou J.R., Dewulf W., On the Complementarity of TRIZ and Axiomatic Design: From Decoupling Objective to Contradiction Identification, Proc. of the ETRIA TRIZ Future Conference 2006, Kortrijk, Oct. 2006, ISBN 90-77071-05-9, Vol.1, pp 1-8

[2] Jeswiet J., Micari F., Hirt G., Bramley A., Duflou J. and Allwood J., Annals of CIRP- Manufacturing Technology, Vol 54/2/2005, p. 623-650

[3] Allwood J.M., King G.P.F., Duflou J., A Structured Search for Applications of the Incremental Sheet Forming Process by Product Segmentation, Proc I Mech E, Part B, Journal of Engineering Manufacture, Vol 219, No. B2 (2005), pp 239-244

[4] Matsubara, S. Incremental Backward Bulge Forming of a Sheet Metal with a Hemispherical Tool, J. of the JSTP, vol. 35, 1994, pp. 1311-1316.

[5] Allwood J.M., Houghton N.E., Jackson K.P., The Advanced Materials Research, Vols 6-8, 2005, pp 471-478

[6] Me H., Smukala V., Dewald O., Zhang J., Two Point Incremental Forming with Two Moving Forming Tools, Key Engineering Materials Vol. 344, 2007, pp 599-605

[7] Suh, N.P., 1988, The principles of Design, Oxford University Press

[8] Neugebauer R., Altan T., Geiger M., Kleiner M., Sterzing A., Sheet Metal Forming at Elevated Temperatures, Annals of the CIRP, 55/2, 2006, pp 793-816.

[9] Young, J.K., Skuratovich, A., Pyeong, K. C., TRIZ Applied to Axiomatic Design and Case Study: Improving Tensile Strength of Polymer Insulator, Proceedings of the TFC2004 Conference, Firenze, November 2004

[10] Shin, G.-S., Park G.-J., 2006, Decoupling Process of a Coupled Design Using the TRIZ, Proceedings of the 4th Internat. Conf. on Axiomatic Design, ICAD2006, Firenze, June 2006

[11] Mann, D., 2002, Hands-on Systematic Innovation, CREAX Press, Ieper, Belgium